Cosmic Rays from Gamma Ray Bursts in the Galaxy

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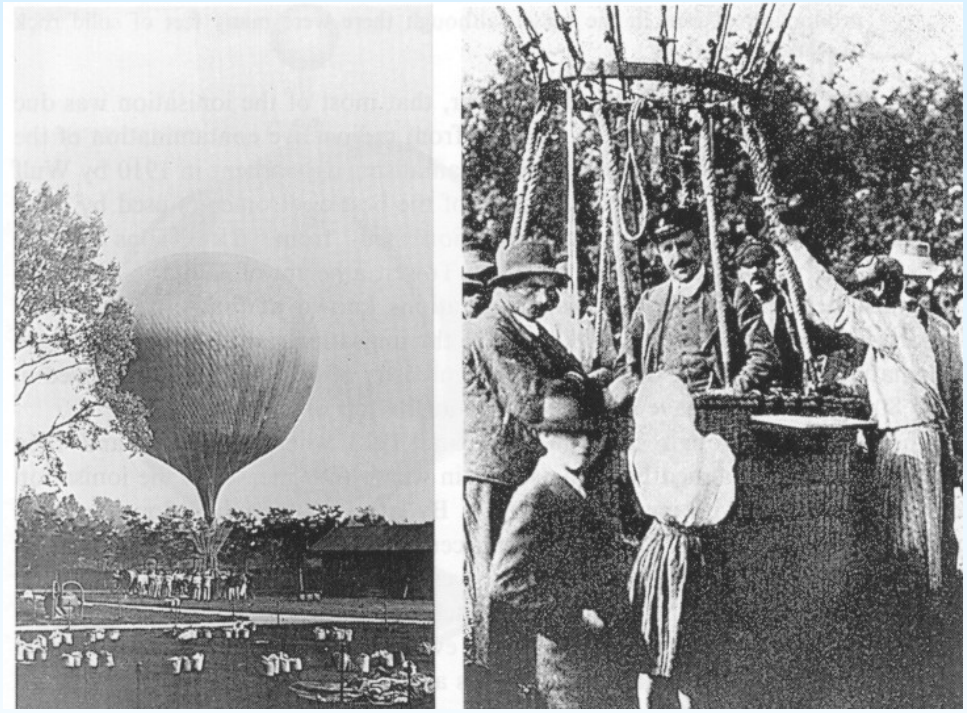
- We have developed a numerical simulation model of cosmic ray propagation from gamma-ray burst (GRB) jets in the magnetic field of the Milky Way galaxy.
- An intensive Euler's method is used to solve for the equations of motion of cosmic ray protons and ions, and protons formed from neutron decay.
- The flux of cosmic-ray neutrons and protons detected in the vicinity of Earth is calculated for different cosmic ray energies and locations of GRB/cosmic ray sources in the Galaxy.
- Cosmic rays from GRBs could explain extinction events in the early history of the Earth, and possible sources of 10^{18} eV cosmic ray anisotropies towards the center of our Galaxy.

Charles Dermer

(NRL)

Cosmic Rays: Highest Energy Particles in Nature

- 1912: Victor Hess: Discharge of electroscope increases with altitude (implies highly penetrating radiation from space)



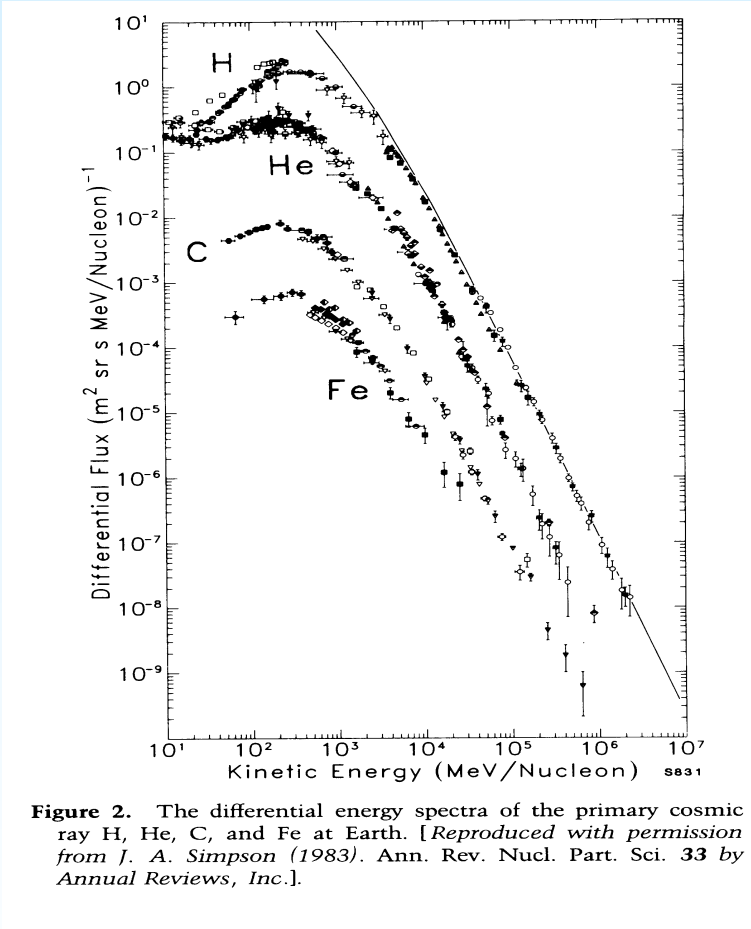


Figure 2. The differential energy spectra of the primary cosmic ray H, He, C, and Fe at Earth. [*Reproduced with permission from J. A. Simpson (1983).* Ann. Rev. Nucl. Part. Sci. **33** *by Annual Reviews, Inc.*].

- Cosmic rays are thought to be accelerated by supernova remnant shocks

Supernovae: Collapsing Stars

- Nuclear Burning in Massive (more than ~8 Solar Masses) Stars leads to an Iron Core
- When the Star runs out of Fuel, the Iron Core Collapses
- Most supernovae collapse to form

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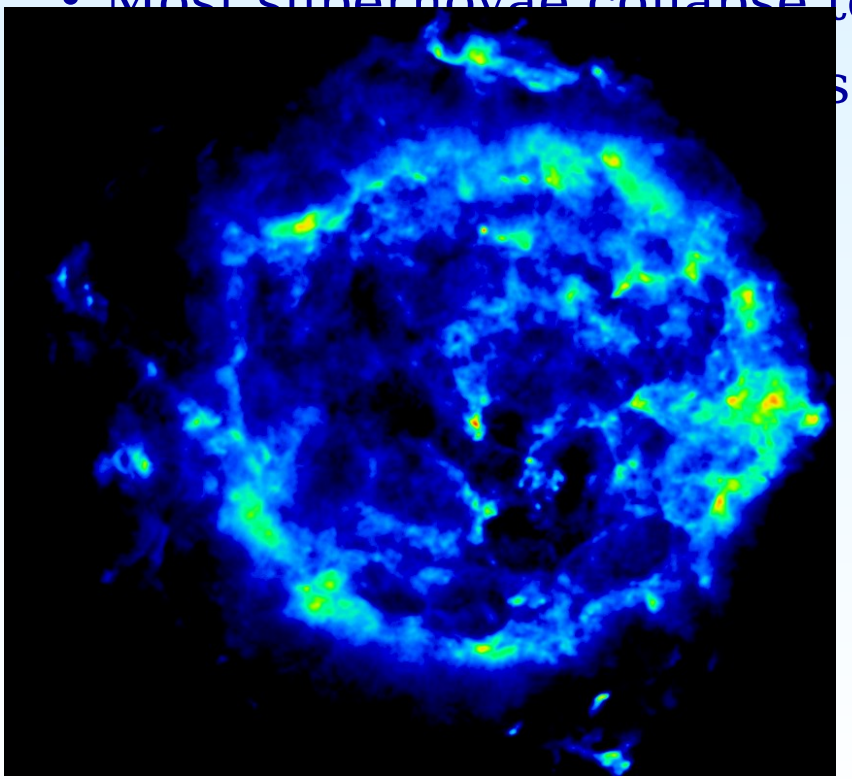
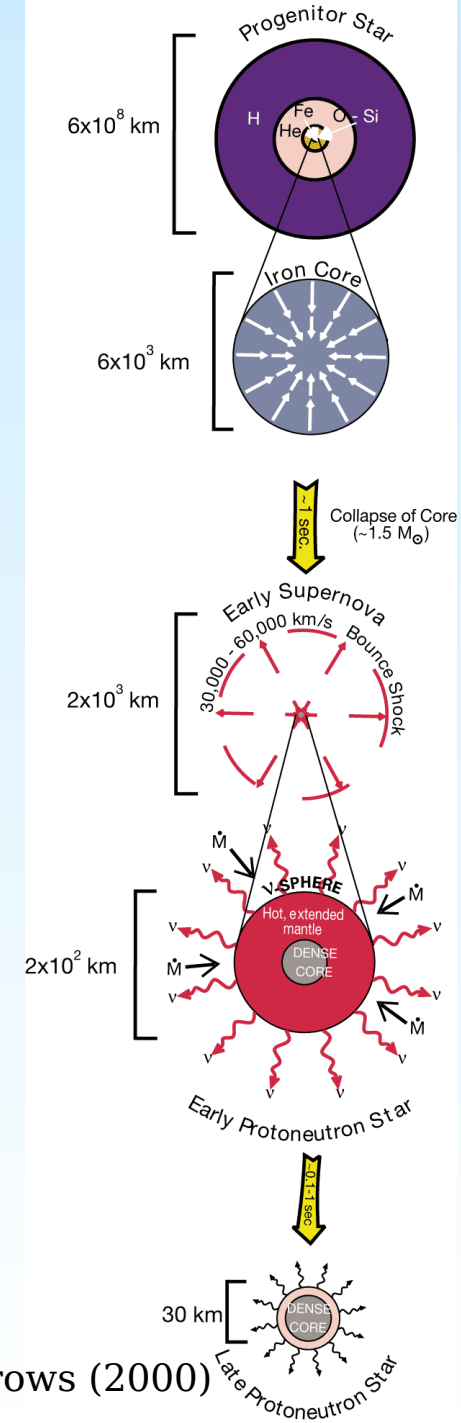


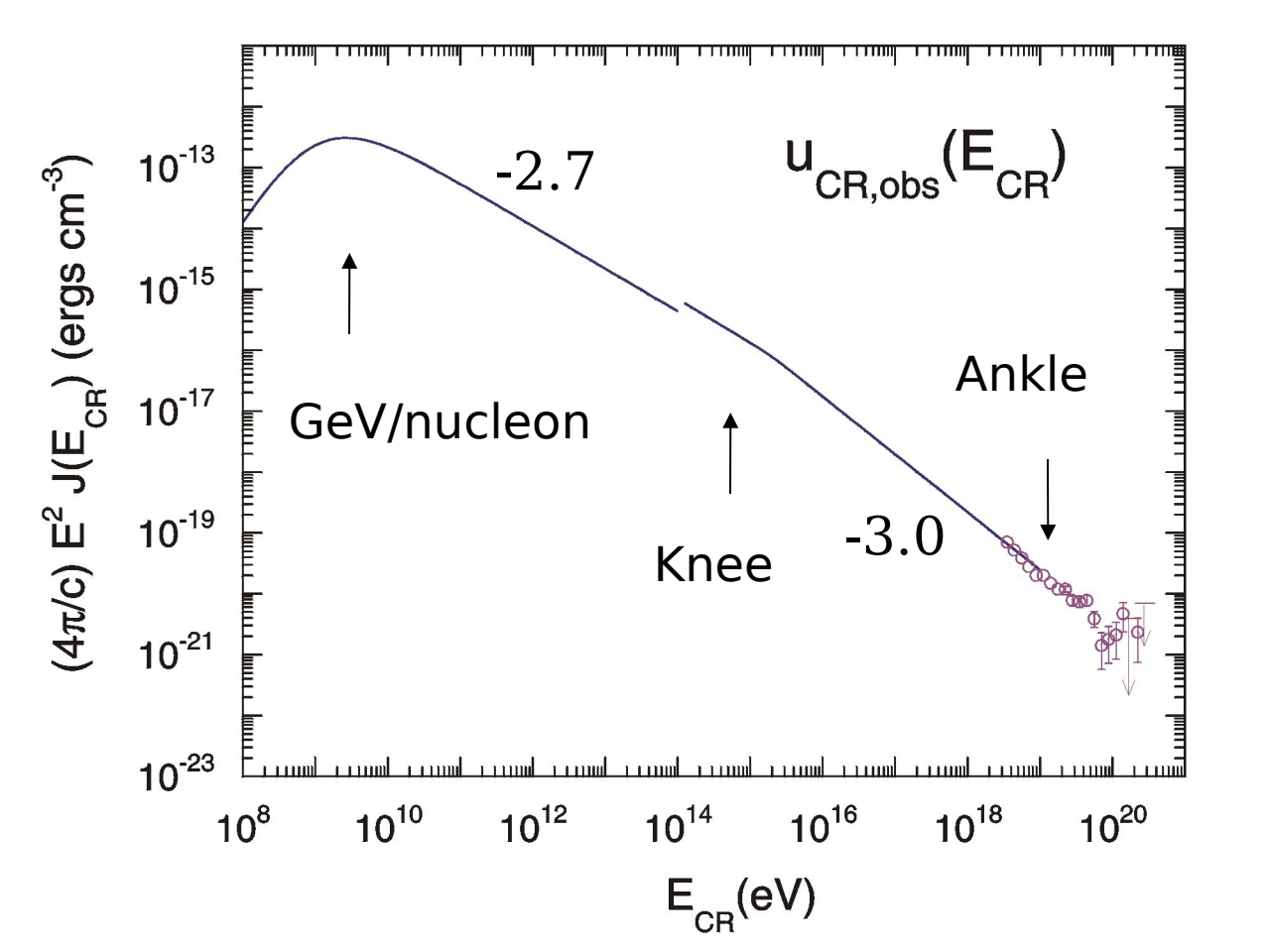
Cassiopiea A
Supernova Remant



Burrows (2000)

Cosmic Rays to the Highest Energies

- Origin of very highest energy cosmic rays is unknown

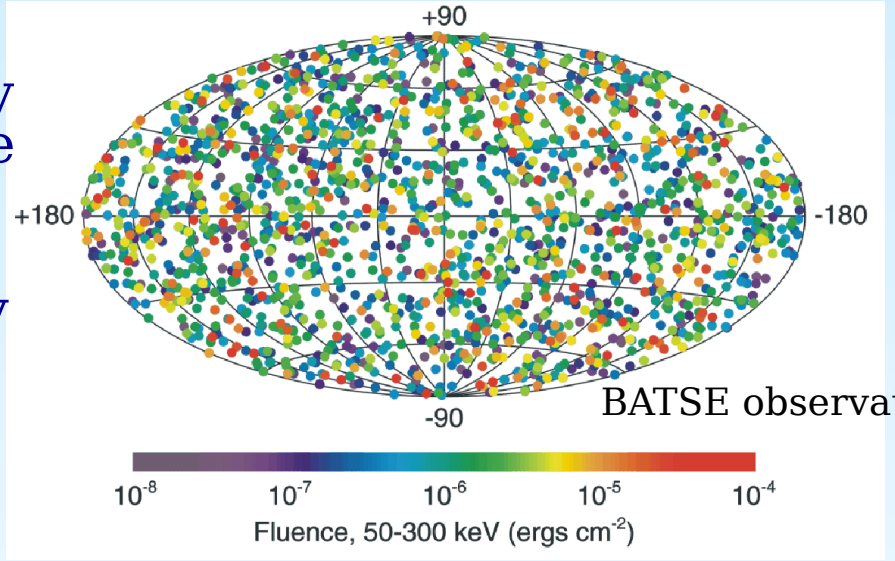


Gamma Ray Bursts: Stellar Collapse to a Black Hole

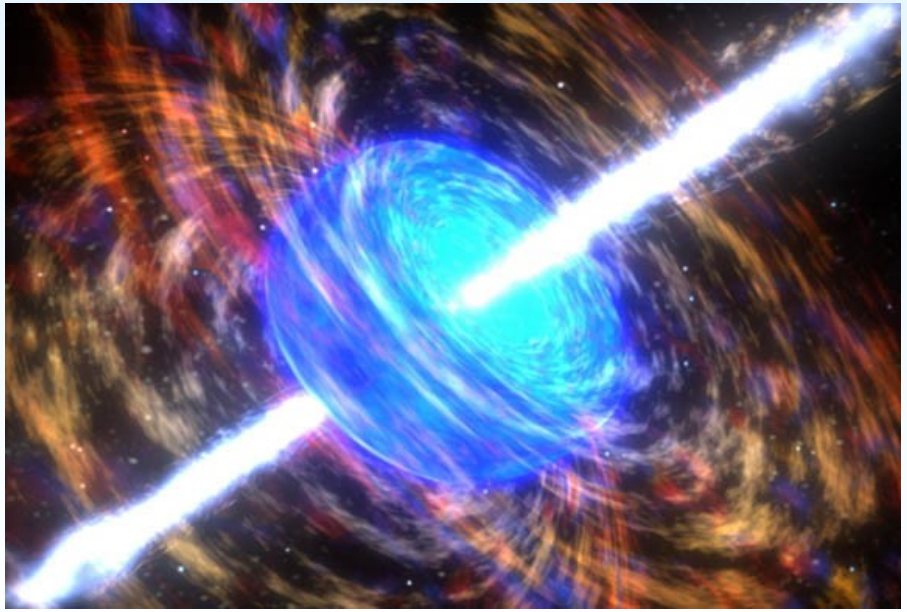
- Gamma-ray bursts are very energetic explosions that are detected from all directions

- The ones we observe today occurred at cosmological distances, and therefore release enormous amounts of energy (if radiated isotropically, some would emit the entire rest-mass energy of the Sun emitted in a few minutes)

- GRBs are thought to be produced in supernovae explosions where the neutron pressure of the massive cores is in sufficient to support the star against collapse to a black hole

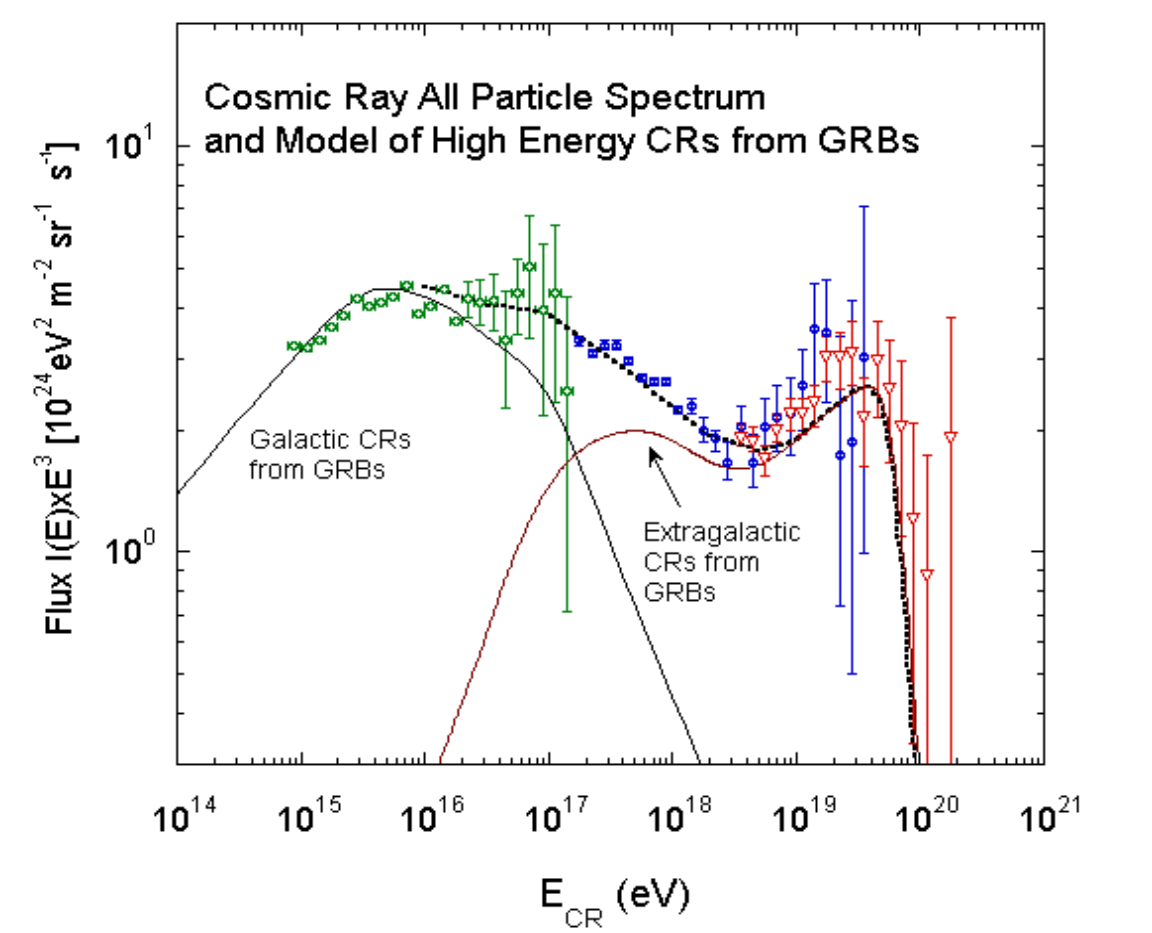


BATSE observations of GI



Gamma Ray Bursts Accelerate High Energy Cosmic Rays

- Model of Wick, Dermer, Atoyan (2004): Cosmic Rays with energies below knee at ~3x10^{15} eV are made by supernovae that collapse to neutron stars; cosmic rays with higher energies made by GRBs in our Galaxy and throughout the Universe



Numerical Simulation Model of Cosmic Rays from GRBs

We have developed a numerical simulation model of cosmic ray propagation from jetted GRBs in the Milky Way

$$\frac{d}{dt}(\gamma m\vec{v}) = \frac{\vec{q}}{c}\vec{v}\times\vec{B}$$

Larmor radius of a particle spiraling in a magnetic field

$$r_L = \frac{mc^2\gamma}{qB} \approx \frac{\gamma/10^9}{B(\mu G)}\,kpc$$

Magnetic Field Model of the Galaxy

Cosmic rays move in response to a large-scale magnetic field that traces the spiral arm structure of the Galaxy, and to pitch-angle scattering with magnetic turbulence in the Galactic magnetic field.

Disk magnetic field:

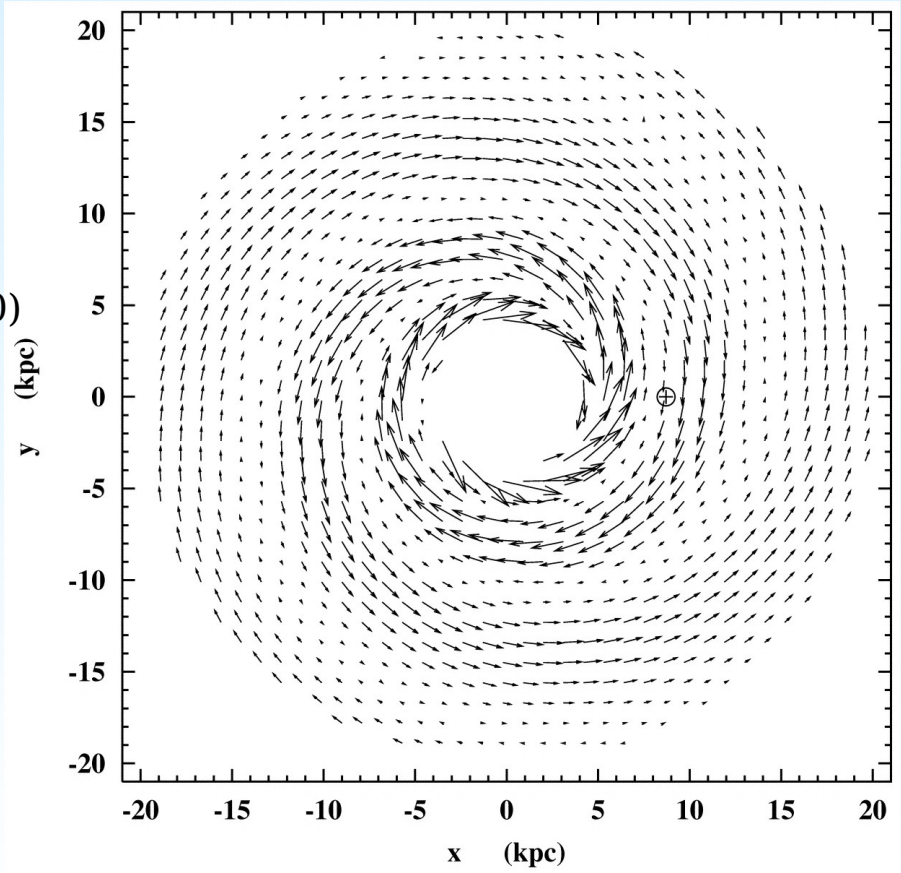
$$B(r,\varphi) = B_o\left(\frac{R_\oplus}{r}\right)\cos\left(\varphi - \beta \ln\frac{r}{R_o}\right)$$

Alvarez-Muniz, et al. (2000)

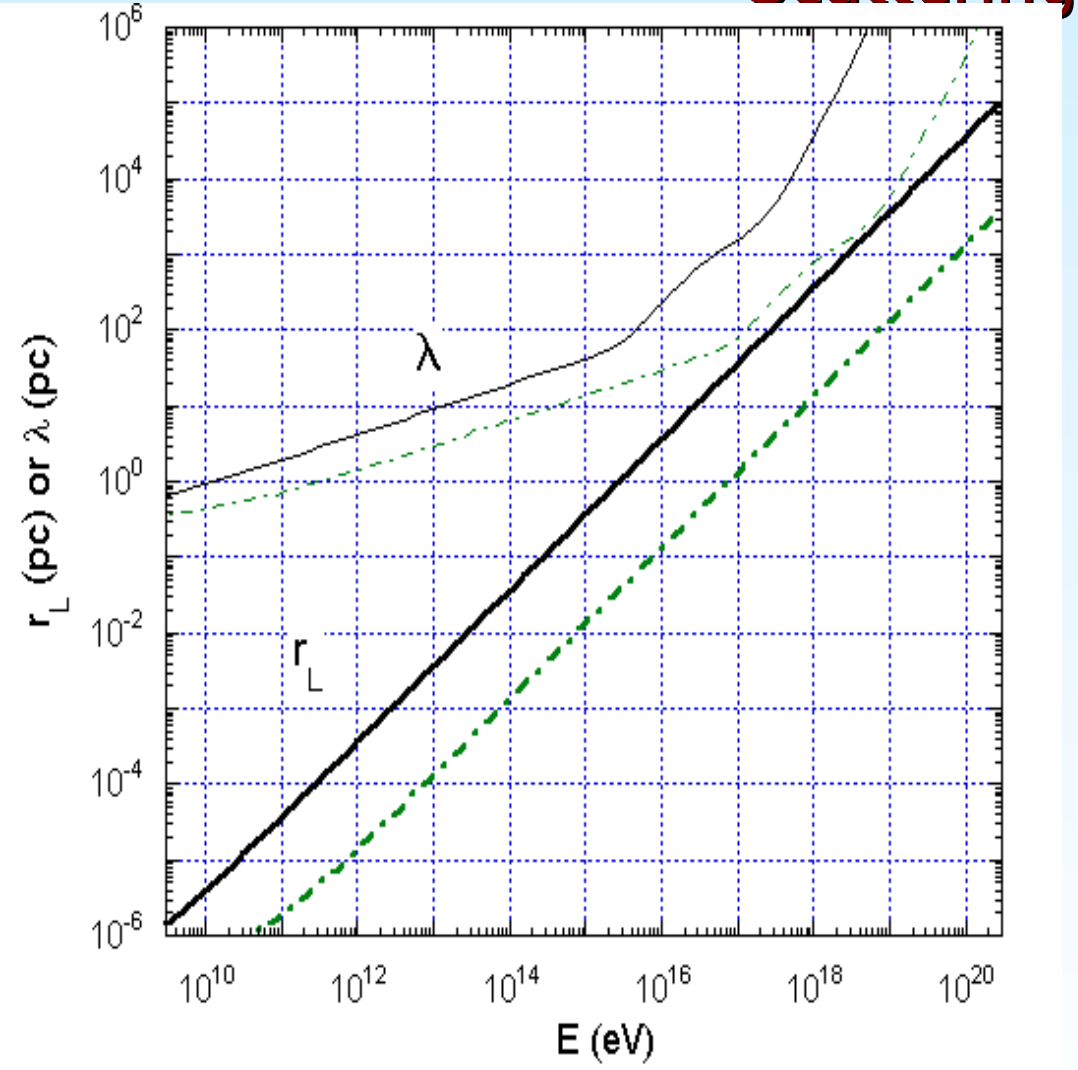
The typical Galactic magnetic field near Earth is 3-4 μGauss

An intensive Euler's method is used to solve for the equations of motion of cosmic ray protons and ions, and protons formed from neutron decay.

Figs. 1 and 2



Diffusion of Cosmic Rays due to Pitch Angle Scattering



Cosmic rays scatter due to wave turbulence that deflects the particles (pitch-angle scattering) and causes them to execute a random walk

Diffusion through stochastic gyro-resonant pitch-angle scattering. Mean free path for being deflected by $\pi/2$

$$\lambda = \frac{U_B}{k\bar{w}(k)} r_L ; k = 1/r_L$$

Figs. 3 and 4

Cosmic Ray Neutrons

Neutrons are also formed in high-energy cosmic ray sources

Neutrons decay on time scales of 920γ seconds, due to time dilation

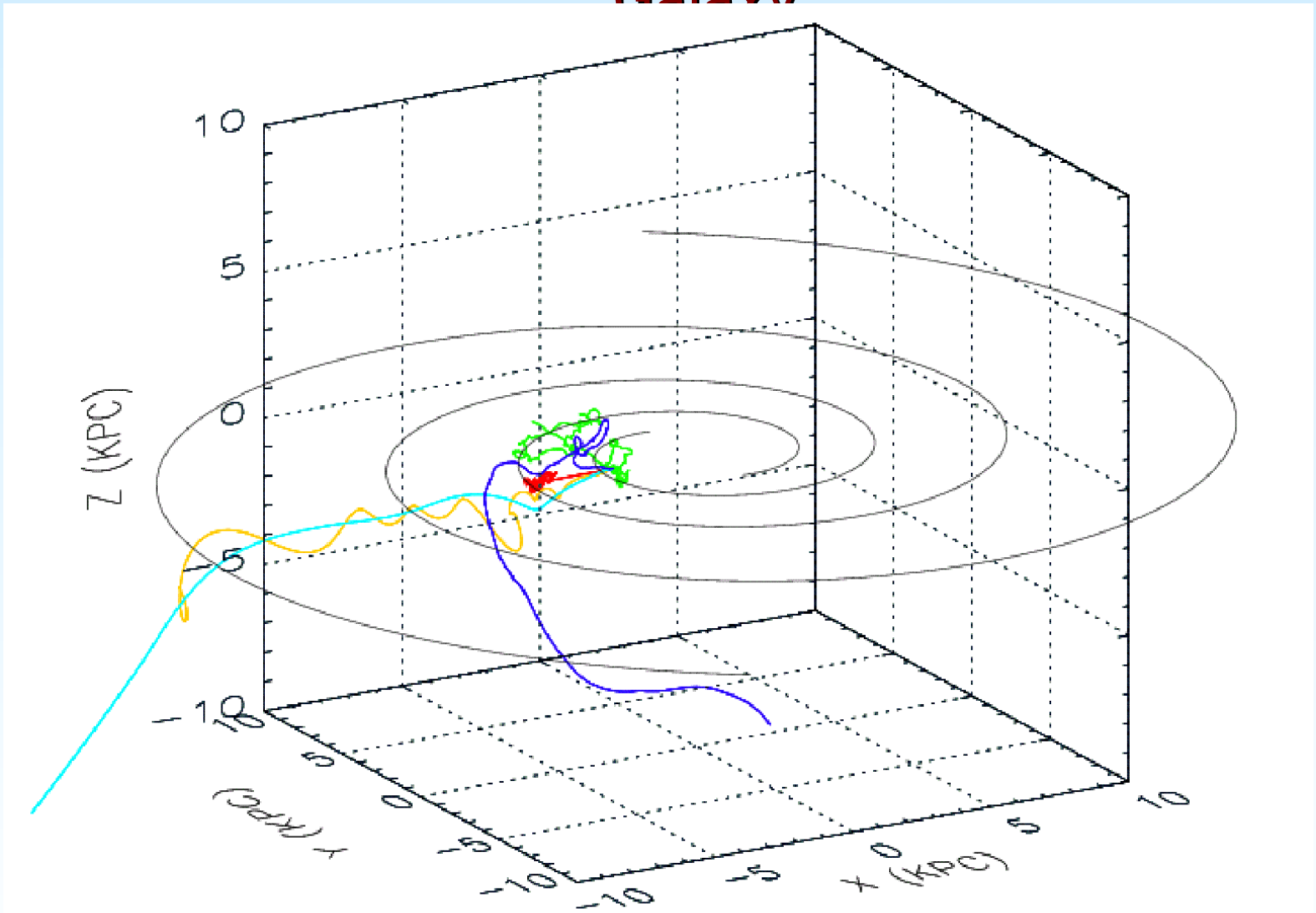
(about 1 kpc for $\gamma=10^8$), and then gyrate in magnetic field $r_n \cong ct_n\gamma \cong (\gamma/10^8)kpc$

Cosmic ray neutrons decay over a pathlength

$$n \rightarrow p + e^- + \nu_e$$

Figs. 5

Trajectories of Cosmic Rays in the Galaxy



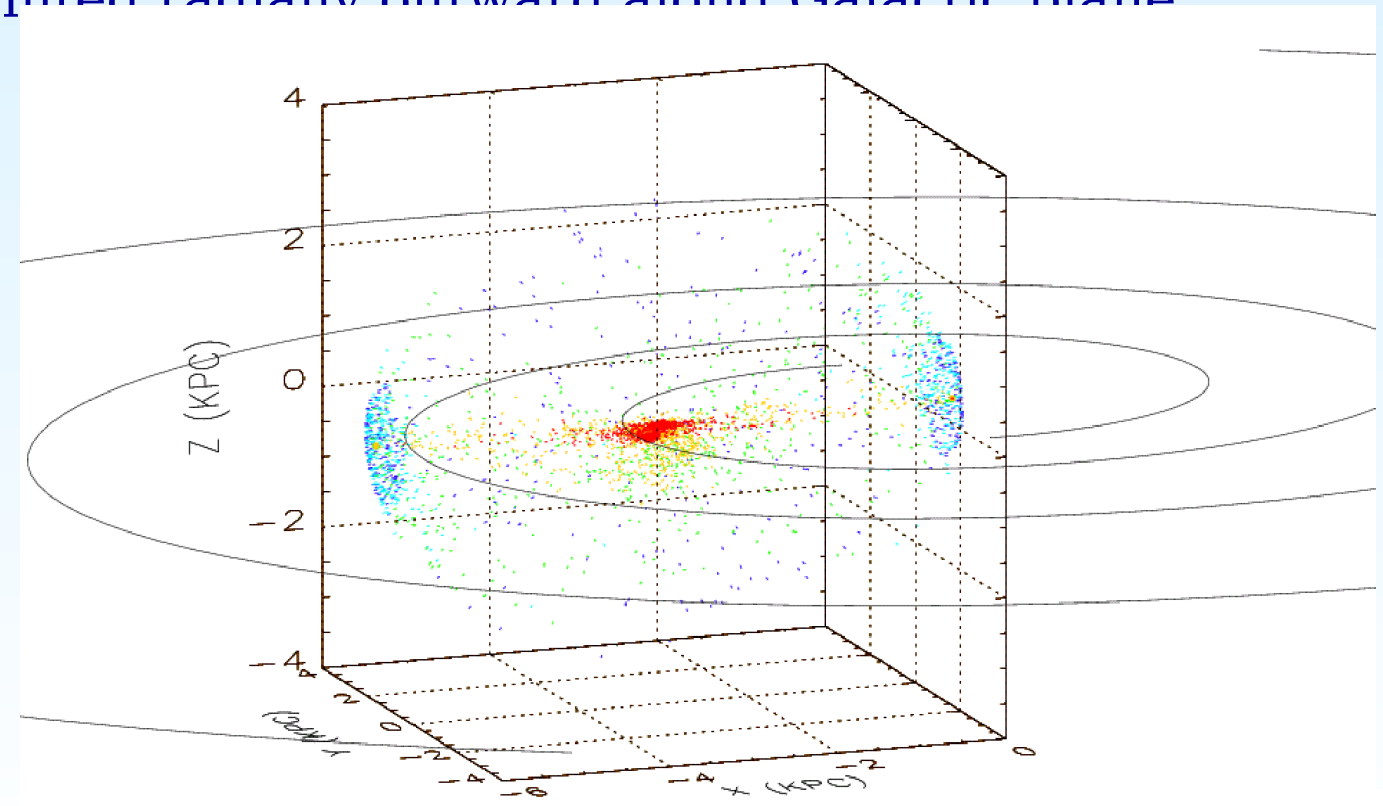
Cosmic Rays from GRBs

GRB located at 3 kpc from center of the Galaxy

GRB emission is jetted with jet opening angle of 0.1 radian

Jet is pointed radially outward along Galactic plane

Figs. 6 and 7



Rate of Irradiation Events by GRBs

Fluence referred to daily Solar energy flunce

for significant effects on biology. Using constant energy reservoir result implies

where 10 yr is the mean time between galactic GRBs, and the GRB distance is

$$\phi = S\phi_{\circ} = 1.2\times10^{-11} S\ ergs\ cm^{-2}$$

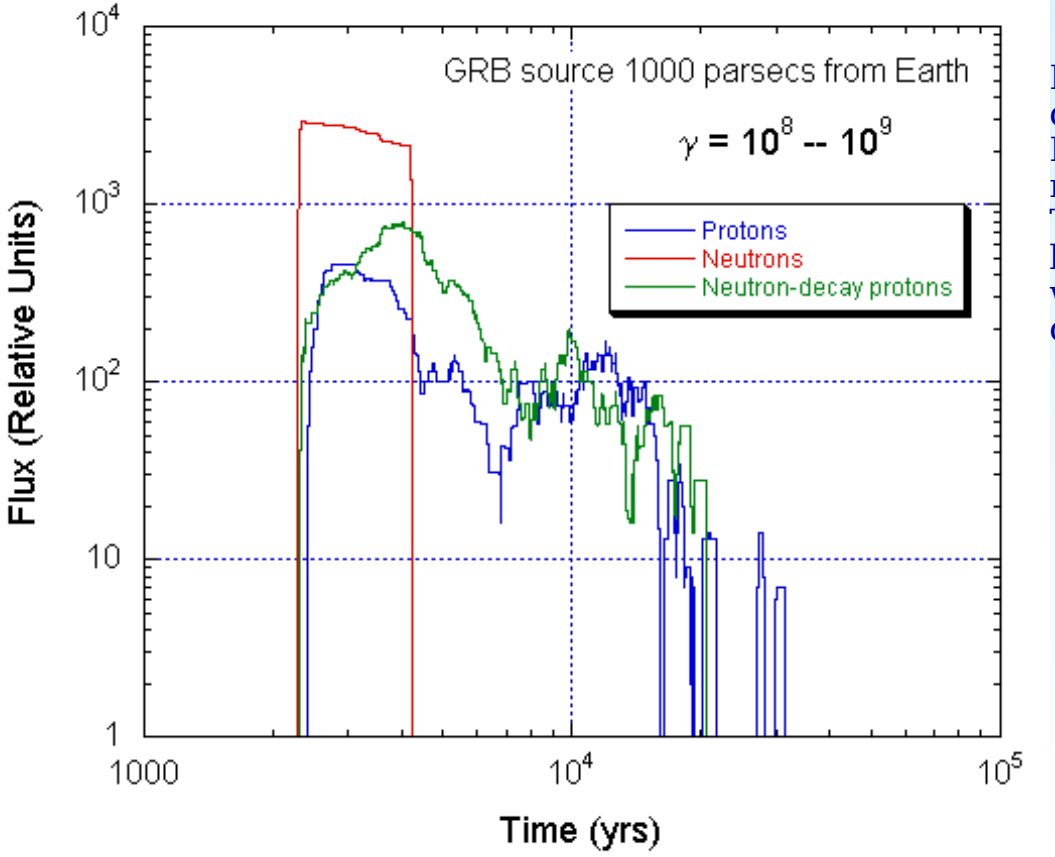
$$S > 10^{-3}$$

$$\dot{N}(>S) \approx \frac{0.03}{R_{15}^{2}} \frac{E_{51}}{S t_{4}}\ Gyr^{-1},$$

$$R_s \approx \frac{120}{(\theta_j/0.1)} \sqrt{\frac{E_{51}}{S}}\ pc$$

Flux of Cosmic Rays from GRB Jet Pointed towards the Earth

The time-dependence of the flux of cosmic ray neutrons and protons detected in the vicinity of Earth is calculated for different cosmic ray energies and GRB locations in the Galaxy.

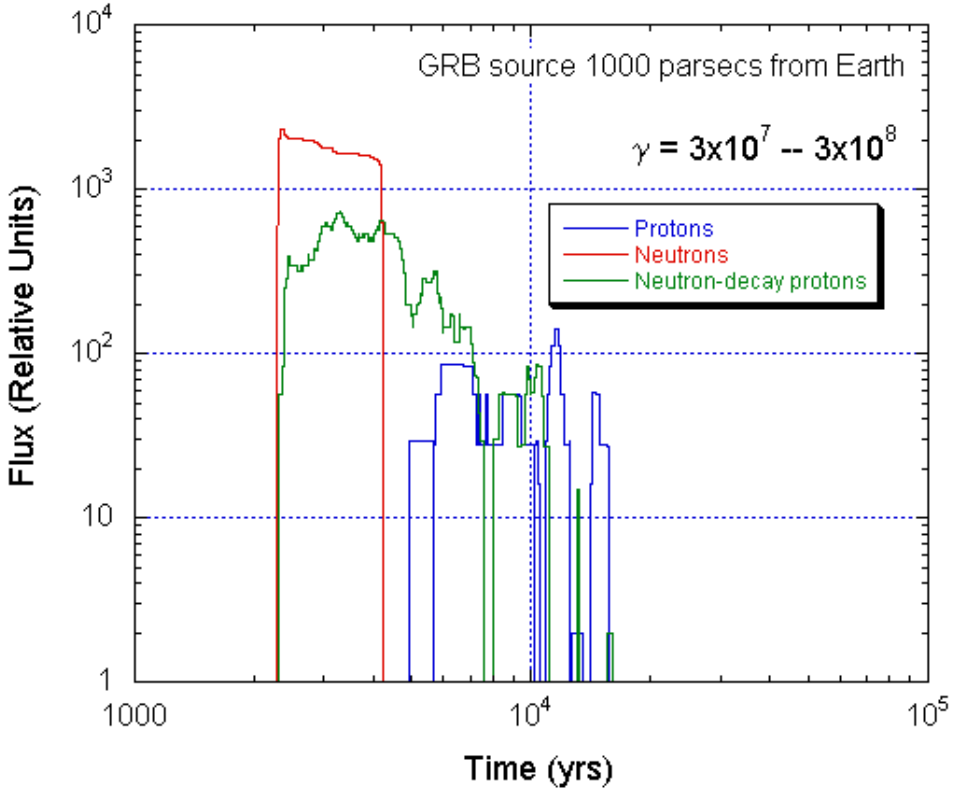


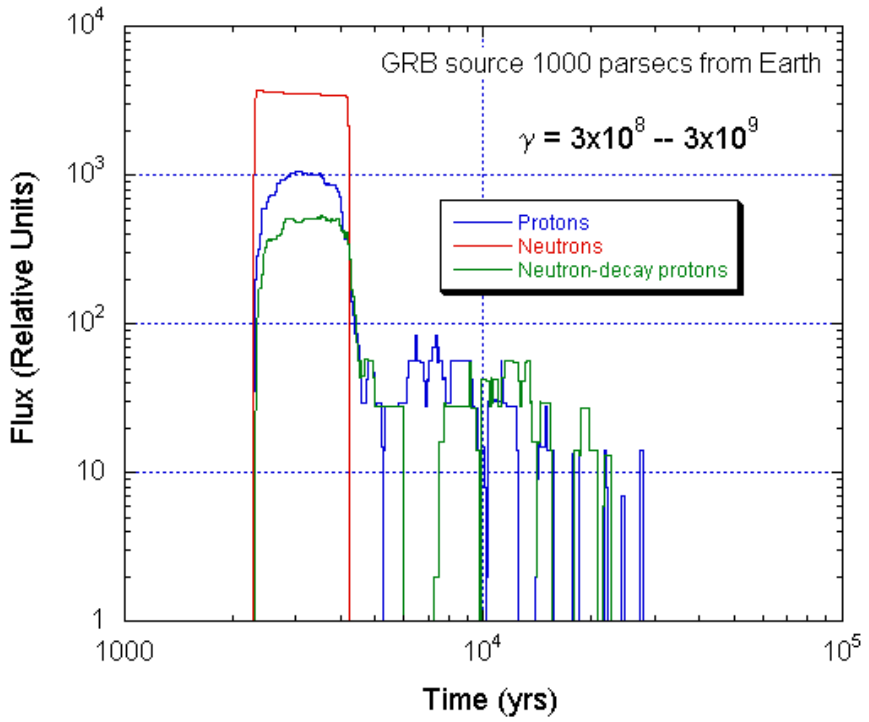
Fluxes of cosmic ray neutrons, neutron-decay protons, and protons passing near Earth as a function of time for cosmic ray Lorentz factors between 10^8 and 10^9. The source of high-energy cosmic rays is located 1000 parsecs from the Earth, with the GRB jet pointed in our direction.

Phases of Cosmic Irradiation from a GRB Jet

As many as three phases of cosmic ray irradiation are found:

1. prompt neutron (and gamma-ray) flux,
2. neutron-decay protons,
3. cosmic ray protons produced at the GRB source.





Effects of Cosmic Rays from Gamma Ray Bursts

Extinction episodes in the Ordovician Epoch

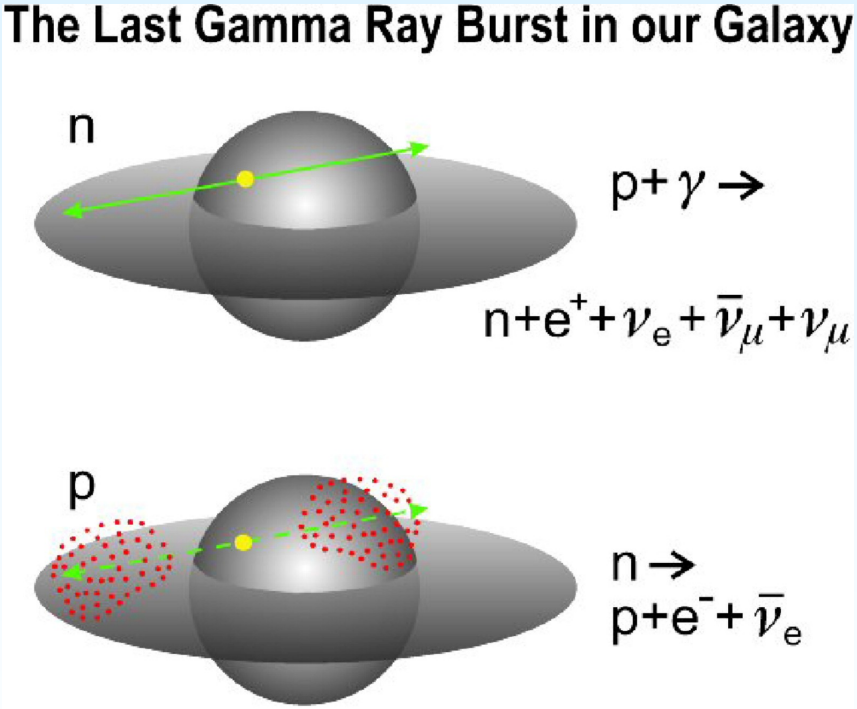
Melott et al. (2004) suggest that a GRB pointed towards Earth produced a lethal flux of high-energy photon and muon radiation flux that destroyed the ozone layer, killed plankton, and led to trilobite extinction

However, geological evidence points toward two pulses; a prompt extinction and an extended ice age.

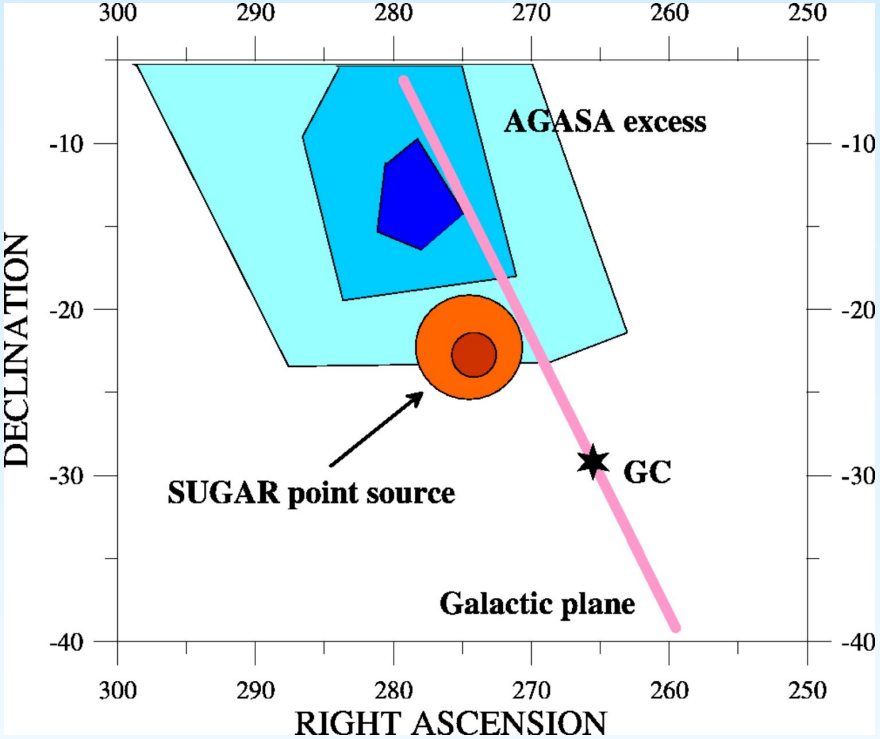
The prompt neutrons and gamma-rays from a GRB could have produced the prompt extinction. The delayed cosmic rays could have produced the later ice age

Cosmic Ray Sources in the Inner Galaxy

Our model can be used to test models for high-energy (10^{18} eV) cosmic ray sources towards the Galactic Center



Biermann et al. (2004)



However, duration of a cosmic-ray neutron event from a GRB is short compared to the mean lifetime between GRBs

Conclusions

- GRBs are theorized to accelerate the highest energy cosmic rays
- GRBs occur once every ~10,000 years in the Milky Way
- About once every 300 Myrs, a GRB will irradiate the Earth and cause mass extinction events
- It seems unlikely that cosmic rays from impulsive GRBs make cosmic ray excesses (if real!) towards galactic center